

The Planetary Nebulae Luminosity Function and distances to Virgo, Hydra I and Coma clusters

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Abstract. The luminosity function of planetary nebulae populations in galaxies within 10 – 15 Mpc distance has a cut-off at bright magnitudes and a functional form that is observed to be invariant in different galaxy morphological types. Thus it is used as a secondary distance indicator in both early and late-type galaxies. Recent deep surveys of planetary nebulae populations in brightest cluster galaxies (BCGs) seem to indicate that their luminosity functions deviate from those observed in the nearby galaxies. We discuss the evidence for such deviations in Virgo, and indicate which physical mechanisms may alter the evolution of a planetary nebula envelope and its central star in the halo of BCGs. We then discuss preliminary results for distances for the Virgo, Hydra I and Coma clusters based on the observed planetary nebulae luminosity functions.

Keywords. Stars: AGB and post-AGB. (ISM:) Planetary nebulae: general. Galaxies: elliptical and lenticular, cD

1. Introduction

Most of the stars in the mass range 1 to 8 M_{\odot} go through the planetary nebulae (PN) phase during the final stages of their lives, before they become white dwarfs. During this phase, the nebular shell of a PN is able to convert the UV ionizing photons into various line emissions, from the UV to the optical and down to the NIR. Up to 15% of the UV energy emitted by the central star is re-emitted in a single line, the [OIII] λ 5007 Å line, which is the brightest optical emission of a PN (Dopita *et al.* 1992).

When observed in our own Milky Way galaxy, the planetary nebula's shells and [OIII] emission are spatially resolved. In M31 and beyond, PNs are spatially unresolved sources of green light, thus the whole [OIII] flux F_{5007} emitted from a PN shell can be integrated and a m_{5007} magnitude is computed as (Jacoby (1989)):

$$m_{5007} = -2.5 \log F_{5007} - 13.74 \quad (1.1)$$

For a PN population observed in external galaxies, we can then derive the PN luminosity function (PNLF).

The PNLF was measured for PN populations in early and late-type galaxies within 10–15 Mpc distance (see Ciardullo *et al.* 2002 for a review) with the following properties:

- The PNLF shows a cut-off at the bright end, whose absolute magnitude is $M^* = -4.51$.
- The shape of PNLF and the cut-off at bright magnitudes are observed to be invariant

in galaxies of different morphological types, either star-forming or quiescent, within 10 – 15 Mpc distance.

Thus the PNLF is used efficiently as a secondary distance indicator, with some important role in the investigation of systematic biases, because it represents one of the few methods that can be applied to both early and late-type galaxies.

The PNLF is empirically shown to follow the analytical formula

$$N(m_{5007}) = C \times e^{0.307m_{5007}} \times [1 - e^{3(m^* - m_{5007})}] \quad (1.2)$$

(Ciardullo *et al.* 1998) where m^* is the apparent magnitude of the bright cut-off. This analytic formula combines the observed behavior at the bright end, which is believed to originate from the most massive, $M_{core} \simeq 0.7M_{\odot}$, surviving stellar cores (Ciardullo *et al.* 1989, Marigo *et al.* 2004), and the slow PN fading rate caused by the envelope expansion, at the faint end (Heinze & Westerlund 1963).

It is an open question whether more physics is required to describe PN populations in massive galaxies than what is captured by the analytical formula $N(m_{5007})$ in eq. 1.2.

2. Physics of the PNLF

The theoretical basis for the $N(m_{5007})$ analytical formula is a population of uniformly expanding, homogeneous spherical PNs ionized by non-evolving central stars. The observed invariance of M^* also seems to indicate that the most massive surviving stellar cores all have the same mass, regardless of the age and metallicity of the parent stellar population. Each of these hypotheses may turn out to be violated in different environments, and we discuss each possibility in turn.

Constancy of M^* – A PNs peak flux is proportional to its core mass (Vassiliadis & Wood 1994). The core mass of a PN is proportional to its turnoff mass (Kalirai *et al.* 2008). The turnoff mass of a stellar population decreases with age (Marigo *et al.* 2004). Simple stellar population theory would then predict that the absolute magnitude of the PNLF at the bright cut-off should become fainter already in a 1 Gyr old population, and up to four magnitude fainter in 10 Gyr old stellar population.

Uniformly expanding, homogeneous spherical shells – The nebular shell may not be spherical, as observed for many MW PNs, not expanding uniformly, and not optically thick. The presence of a hot ISM in evolved stellar populations may also effect the mass loss during the AGB evolution and the properties of the ionized PN shell (Dopita *et al.* 2000, Villaver & Stanghellini 2005). The interaction between nebular shell and hot gas may also decrease the visibility lifetime of a PN, τ_{PN} , which in turns decreases the total number of PNs associated with a given bolometric luminosity emitted the parent stellar population (Buzzoni *et al.* 2006).

Non evolving central star – Simple stellar population theory predicts low-mass cores $M_{core} \leq 0.55M_{\odot}$ (Buzzoni *et al.* 2006) in an old stellar population, as the one detected in the M87 halo (Williams *et al.* 2007). For such low mass cores, τ_{PN} may be shorter than 3×10^4 yrs (Buzzoni *et al.* 2006) because the time required for the excitation of the nebular envelope increases, and by the time it happens, the density in the nebular shell may be too low for any significant [OIII] emission. Furthermore, part of the stellar population with $M_{core} \sim 0.52M_{\odot}$ may omit the PN phase entirely (Blöcker 1995). These evolved stars may provide an enhanced contribution to the hotter horizontal branch (HB) and post - HB evolution (Greggio & Renzini 1990), as directly observed in M 32 and in the bulge of M 31 (Brown *et al.* 1998, 2000).

Physical conditions which violate the hypotheses embedded in the analytical formula $N(m_{5007})$ may particularly occur in the halos of BCGs galaxies at the center of massive

clusters because the stellar populations are old and immersed in a high density ICM. We then expect to find deviations of the observed PNLf for these systems, the closest one being the BCG galaxy in the Virgo cluster, M87. Similar physical conditions are expected for PN in environments like NGC 3311 in the Hydra I cluster, and the Coma cluster BCGs.

3. The PNLf in the M87 outer halo

The nearby clusters have a very important role in the cosmological distance ladder. The measurement of the distance to the Virgo cluster by the Key project was crucial for the determination of the Hubble constant. There were several projects aimed at the measurement of the PNLf distance to the Virgo elliptical galaxies (see Ciardullo *et al.* 2002 for a review). The most extended PN survey in the M87 halo was that carried out by Ciardullo *et al.* (1998) covering a $16' \times 16'$ field, centred on M87.

The empirical PNLf measured in M87 halo from a sample of 338 PN deviates significantly from the analytical formula $N(m_{5007})$ for a distance modulus of $(m - M) = 30.79$ (Ciardullo *et al.* (1998)). The deviations are such that 1) the PNLf shape is different for the inner $< 4'$ and the outer regions $> 4'$, with the PN candidates in the halo having brighter m_{5007} than the cut-off expected for $(m - M) = 30.79$, and 2) the PNLf for the outer sample is not drawn from a population following eq. 1.2, at the 99% level according to KS tests. At that time, the PNLf deviations were explained in terms of a uniform Intracluster PN (IPN) population, which extended 2 Mpc in front of the M87 halo PN population, so that the overluminous PNs could be explained as IPNs.

There is some tension in this proposed scenario. The spectroscopic follow-up of PNs bound to the M87 halo showed that these PNs have a brighter cut-off, $m^* = 26.2$, than PNs in the inner regions, for which $m^* = 26.35$ (Arnaboldi *et al.* 2008). Furthermore the extended survey carried out by Castro-Rodriguez *et al.* (2009) showed that the IPN population in the Virgo cluster is associated with its densest regions, and IPNs extend to at most 0.4 Mpc in front of M87. In Fig. 1 we show the surface brightness profile for the ICL in the Virgo cluster; it illustrates that the ICL and IPN population are concentrated around M87 and in the densest regions of the Virgo cluster.

In 2010 we started a new project to survey PN in M87, covering the whole halo out to 150 kpc. It entails an imaging survey with SuprimeCAM@Subaru, with the aim at covering 0.5 deg^2 in the M87 outer halo, and a spectroscopic follow-up with FLAMES@VLT of the selected candidates. PN candidates are identified using deep [OIII] and off-band V images: they are selected as point like [OIII] sources with a color excess $[OIII] - V = -1$ and no continuum (Arnaboldi *et al.* 2002).

The SuprimeCAM observations for the PN survey in M87 were taken with a total exposure time in the narrow band [OIII] filter of about 4 hrs and a total exposure time in the off band (V band) of about 1 hr, for each pointing. Analysis of the data is on-going; the properties of the PNLf from this extended PN sample, both in area and depth, are presented in Longobardi *et al.* (2012), in prep.

4. Detecting PN beyond Virgo

The brightest PNs in the Hydra I cluster at 50 Mpc distance have fluxes of $7.8 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ (~ 7 photons/min on 8m tel.). In the Coma cluster, fluxes are four times fainter. These very faint fluxes cannot be detected using a narrow band filter because the sky noise in a $30 - 40 \text{ \AA}$ centred on the redshifted [OIII] PN emission is of the same order of the signal we want to detect. A step forward for the detection of PN in

elliptical galaxies in clusters at distances larger than 15 Mpc is the Multi Slit Imaging Spectroscopy Technique (MSIS).

MSIS is a blind search technique, that combines a mask of parallel multiple slits with a narrow band filter, centred on the redshifted [OIII] 5007 Å line at the Hydra I/Coma mean systemic velocity, to obtain spectra of all PNs that lie behind the slits (Gerhard *et al.* 2005). The sky noise at the PN emission line now comes from a spectral range of only a few Å, depending on slit width and spectral resolution (Arnaboldi *et al.* 2007). Several tens of PNs were detected using the MSIS observations in the Hydra I (Ventimiglia *et al.* 2011) and Coma (Gerhard *et al.* 2007) clusters.

We can then use the PNLf from the MSIS data-sets to determine the distances of Coma and Hydra I relative to the Virgo cluster, which may reduce systematics errors in the distance measurements to these clusters. This is important because several methods for the measurements of cosmological distances (i.e. fundamental plane, high- z SN) rely on the distance to the Coma cluster for their zero-point.

Because PNs can be observed mostly for BCGs in these clusters, we need more advanced models for the PNLf like those computed by Méndez *et al.* (2008), see also discussion in Sec. 2. Then we need to account for the through slit-convolution and convolution with photometric errors, plus completeness correction; see Ventimiglia *et al.* (2011) for an overview of the procedure. Then the cumulative PNLf is a direct distance indicator that can be used to derive the distances to clusters beyond Virgo.

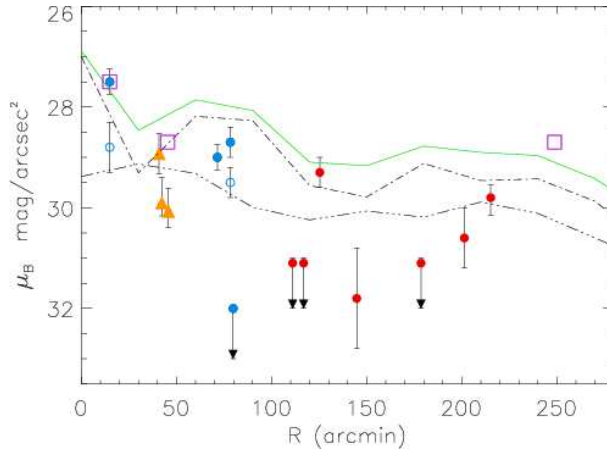


Figure 1. Surface brightness measurement of diffuse light in the Virgo fields (points) compared with the surface brightness profile of the Virgo galaxies averaged in annuli (lines); radial distances are computed with respect to M87. The continuous line represents the radial surface brightness profile from light in Virgo galaxies from Binggeli *et al.* 1987. The dotted-dashed and double dotted-dashed lines correspond to the surface brightness profile associated with giants and dwarf galaxies, respectively. The blue (darker) full dots show the surface brightness measurements in the Virgo core. The open circles at 10' and 80' distances indicate the ICL surface brightness computed from the IPNs not bound to galaxy halos. The triangles represent the surface brightness of the ICL based on IC RGB star counts (Williams *et al.* 2007 and reference therein). The red full dots at distances larger than 80' show several surface brightness measurements and arrows indicate their upper limits. The magenta open squares indicate the surface brightness average values μ_B at 15, 50 and 240 arcmin computed from the measurements of Feldmeier *et al.* (2004); the measurements at 240' are close to M49. The diffuse light is concentrated around M87 and M49, with a sharp decrease at a distance of 80' = 0.4 Mpc. From Castro-Rodriguez *et al.* (2009).

5. Preliminary results

Preliminary distance moduli and distances based on PNLf and MSIS samples are

- Virgo $(m - M)_0 \simeq 30.8$; $D_{\text{Virgo}} \simeq 15$ Mpc
- Hydra $(m - M)_0 \simeq 33.5$; $D_{\text{Hydra I}} \simeq 3.43 \times D_{\text{Virgo}} = 51.5$ Mpc
- Coma $(m - M)_0 \simeq 34.9$; $D_{\text{Coma}} \simeq 6.51 \times D_{\text{Virgo}} = 97.7$ Mpc

The next steps of this project include:

- the use of the observed PNLf in the M87 halo (Longobardi *et al.* 2012, in prep) to test models for PNLf in old stellar populations, including effects on AGB evolution and ionization of PN caused by presence of hot ISM.
- Enlarge the MSIS sample of PN in Coma by including the PN samples from two additional two fields (Arnaboldi *et al.* 2013, in prep).
- Carry out extensive simulation for MSIS (through slit-convolution, convolution with photometric errors; completeness correction) and error estimates on distances (Gerhard *et al.* 2013, in prep).

The project of determining distances to clusters out to Coma using the PNLf is entering into a new, exciting, phase!

6. Acknowledgments

MAR wishes to thank the organizers of the IAU Symposium 289 for the opportunity to give this talk.

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